

Lyman-break galaxies: are they young spheroids?

F. Matteucci¹ and A. Pipino¹

Astronomy Department, University of Trieste, Via G.B. Tiepolo, 11, I-34127, Trieste, Italy

ABSTRACT

We have compared the results from a model for the chemical evolution of an elliptical galaxy with initial luminous mass of $2 \cdot 10^{10} M_{\odot}$ and effective radius of 2 kpc with the recent abundance determinations for the Lyman-break galaxy MS 1512-cB58 at a redshift $z=2.7276$. After correcting the iron abundance determination for the presence of dust we concluded that the observed [Si/Fe], [Mg/Fe], [N/Fe] are consistent with our model when a galactic age between 20 and 35 Myr is assumed. Moreover, the [N/O] ratio also suggests the same age. This age is in very good agreement with other independent studies based on the analysis of the spectral energy distribution suggesting that this object is younger than 35 Myr. Therefore, we suggest that MS 1512-cB58 is a truly young normal elliptical galaxy experiencing its main episode of star formation and galactic wind.

Subject headings: galaxies: abundances, formation and evolution

1. Introduction

Since the discovery of a large population of actively star-forming galaxies at $3 \leq z \leq 3.5$, identified by their red-shifted Lyman continuum breaks at 912\AA in the rest-frame (hereafter LBGs, see Steidel et al. 1996a,b), it has become clear that studying their properties as a whole, as well as their individual spectra, could allow us to obtain information on star formation histories, ages and metallicities of such high redshift objects. This information can then be used to compare the LBGs to present-day galaxies. From Hubble Deep Field and ground-based far-UV spectra, Steidel et al. (1996a,b) found that these galaxies are very similar to nearby star-forming galaxies. The observation of space density, star formation rate, masses, physical sizes and morphologies, led them to the conclusion that the LBGs they discovered could be the progenitors of the spheroidal components of present-day luminous galaxies (i.e. elliptical galaxies or spiral bulges). An argument in favor of ellipticals in clusters as the descendants of LBGs is also given by the strong clustering observed for these objects (Adelberger et al. 1998; Steidel et al. 1998). On the other hand, other authors (Lowenthal

et al. 1997; Sawicki and Yee, 1998; Somerville, Primack & Faber, 2001) favor the idea that LBGs can be sub- L^* galaxies or that they are low mass starbursting objects which later merge to form more luminous galaxies. A crucial test for the nature of LBGs is to measure their masses. The inferred stellar masses for LBGs are in the range $M_* = 10^9 - 10^{11} M_\odot$ with an average mass of $\sim 10^{10} M_\odot$ (Papovich et al. 2001). However, these are only lower limits since they measure the young starburst component. The inferred ages for the starbursting populations range from 30 Myr to 1 Gyr. Again, these are lower limits to the ages of LBGs, since it cannot be excluded that star formation was occurring even before the observed starburst.

By means of near-IR observations, Shapley et al. (2001) studied 81, $z \sim 3$ LBGs and found a strong correlation between the inferred star-formation rates and dust extinction: younger galaxies have more dust and higher star-formation rates than older galaxies. Dustier galaxies are also more luminous. To explain these correlations they proposed an “evolutionary sequence” for LBGs, in which the younger galaxies evolve into the older, less reddened and quiescent ones. They derived ages t_{sf} for LBGs ranging from several Myr to 1 Gyr, and best-fit star-formation rates in the range $\psi(t_{sf}) \sim 5 - 940 \text{ h}^{-2} \text{ M}_\odot \text{ yr}^{-1}$ with a median $\psi(t_{sf}) \sim 45 \text{ h}^{-2} \text{ M}_\odot \text{ yr}^{-1}$. The total masses in stars derived by integrating the average star formation rate over time are $\geq 10^{10} M_\odot$. They detected also evidences of winds and outflows driven by SNe and massive stars, which could enrich the intergalactic medium in metals and energy.

In the following we focus on MS 1512-cB58, the brightest LBG known so far owing to its gravitationally lensed nature. This object is at $z = 2.7276$ and has a luminous mass of $\sim 10^{10} M_\odot$, a star formation rate of $\psi(t_{sf}) \sim 40 \text{ M}_\odot \text{ yr}^{-1}$ (Pettini et al. 2001) and an effective radius of $r_L \sim 2 \text{ kpc}$ (Seitz et al. 1998), for a $\Omega_m = 0.3, \Omega_\Lambda = 0.7, h = 0.70$ cosmology. From the study of MS 1512-cB58 Pettini et al. (2001) derived also the interstellar medium (ISM) chemical abundances. In particular, they concluded that the abundances of O, Mg, Si, P, S are $\sim 2/5$ of their solar values, whereas N, Mn, Fe and Ni are underabundant by a factor of ~ 3 . Depletion into dust, which is known to be present in MS 1512-cB58, probably accounts for some of the Fe-peak element underabundances, but this is not likely to be an important effect for nitrogen. They indicate that MS 1512-cB58 is young with an age, less than the typical timescale for the release of N from intermediate mass stars and Fe from type Ia SNe. They suggest $t_{sf} \leq 300 \text{ Myr}$ while Ellingson et al. (1996) derived an age younger than $\sim 35 \text{ Myr}$ for the starburst in MS 1512-cB58 by means of a fit of the spectral energy distribution (SED). Finally, an outflow involving the bulk of the ISM and proceeding at a speed of $\sim 255 \text{ Kmsec}^{-1}$ seems to be present in MS 1512-cB58. This velocity probably exceeds the escape velocity of the galaxy, thus suggesting that MS 1512-cB58 is probably suffering a galactic wind, although firm conclusions on this point are not possible.

Models for the chemical evolution of elliptical galaxies, which are able to reproduce the observed properties of local ellipticals, assume that most of the star formation in these objects took place several billion years ago and lasted for a period no longer than 1 Gyr, at the end of which a strong galactic outflow occurred. These kinds of models are known as “supernova-driven galactic wind models” for ellipticals and were first introduced by Larson (1974). Supernova-driven wind models including detailed chemical evolution and supernova energetics have been later proposed by Arimoto & Yoshii (1987) and Matteucci & Tornambè (1987) and they were aimed at explaining the mass-metallicity relation and the color-magnitude diagram of ellipticals. A multi-zone, more-refined version of these models was then presented by Martinelli, Matteucci & Colafrancesco (1988). These models are also called “monolithic models” as opposed to “hierarchical models” (see e.g. Kauffmann, 1996), the two main competing pictures for galaxy formation. The main difference between these two scenarios of galaxy formation is that in the first case ellipticals formed in a short timescale (1-2 Gyr) and at very high redshifts ($z \geq 3$) and evolved passively afterwards, whereas in the second case galaxies assembled in a hierarchical fashion. In particular, the hierarchical process took place over a large time interval with the consequence of having active star formation until recently in large ellipticals.

The aim of this letter is to test whether the observed chemical properties of LBGs, and in particular of MS 1512-cB58, can be explained under the assumption that LBGs are normal elliptical galaxies forming at high redshift, and to set independent constraints on the age of this galaxy. In particular, abundance ratios, especially those between elements formed on different timescales, can set important constraints on the age and the nature of high-redshift objects. In Section 2 we describe the chemical evolution model we adopt, in Section 3 we present the model results and their comparison with the observed abundances. Finally in Section 4 some conclusions are drawn.

2. The Model

The elliptical galaxy model we adopted here is a multi-zone model (Martinelli, Matteucci & Colafrancesco, 1998; Pipino et al. 2002), in which the gas collapses into the potential well of a dark matter halo at high redshifts ($z \geq 3$) on free-fall timescales. The star formation rate is very efficient and lasts until the energy injected into the ISM by stellar winds and supernovae (Ia,b and II) triggers a galactic wind which develops first in the most external regions and later in the more internal ones. As a consequence, while the outer regions are suffering an outflow the inner ones are still actively forming stars. This kind of model can account for the abundance and color gradients observed in ellipticals (Menanteau, Jimenez

& Matteucci, 2001). Generally, after the onset of the galactic wind no star formation is assumed to take place in that particular region, thus supernovae (SNe) of type II and Ib, which originate from massive stars, no longer occur whereas SN Ia continue to explode until the present time. In fact, type Ia SNe are believed to originate from white dwarfs in binary systems. Therefore, the evolution of the galaxy, after the onset of the wind, is dominated by type Ia SNe which inject into the ISM heavy elements (mostly iron) and thermal energy.

For the equations of chemical evolution and related details, we direct the reader to the above mentioned papers, while here we recall only the main assumptions of the model. The initial mass function (IMF) is expressed by the classic Salpeter (1955) law: $\varphi(m) \propto m^{-(1+1.35)}$, defined in the mass range $0.1 - 100M_{\odot}$. Given the uncertainties in the knowledge of the mass of this object we assumed several values for the initial luminous mass (gas plus stars) of the galaxy. In this letter we present three cases, with initial luminous masses 10^9 , $2 \cdot 10^{10}$ and $10^{11}M_{\odot}$ and effective radii of 0.5, 2 and 3 kpc (see Matteucci, 1992), respectively. Each galaxy is divided in several concentric shell roughly 0.5 kpc wide.

The star formation rate (SFR) $\psi(t)$ is related to the gas mass by the following equation:

$$\psi(t) = \nu M_{gas}(t) \quad (1)$$

with the efficiency of star formation ν being in the range $15-12 \text{ Gyr}^{-1}$ (see Pipino et al. 2002). In this formulation the star formation rate is maximum at the beginning and then decreases with time, as shown in Figure 1 (where the average star formation rate inside the optical radius of each galaxy is plotted), and strongly depends upon the galaxy mass. The potential energy of the gas is computed by assuming that the galaxy is surrounded by a massive and extended dark matter halo with $M_{dark} = 10 \cdot M_{lum}$ and $\frac{r_L}{r_D} = 0.1$, where r_D represents the radius of the dark matter core (Bertin et al., 1992). The onset of the galactic wind in each zone depends on the time at which the energy, restored by SNe, exceeds the gas binding energy. At this time, t_{GW} , all the gas present in the galaxy starts to be lost. Clearly t_{GW} is extremely sensitive to the assumptions made about the feedback between SNe and ISM. The detailed calculation of the ISM thermal energy due to stellar winds and SNe can be found in Pipino et al. (2002). In that paper we adopted new energetic prescriptions for SNe taking into account the most recent results concerning the evolution of a SN remnant in the ISM. In particular, the most crucial parameter in order to compute the amount of energy transferred by a single SN into the ISM is the cooling time of the remnant. This is the time at which radiative losses cannot be neglected and most of the energy deposited by the shock wave into the ISM, during the adiabatic phase, is lost radiatively. In particular, for type II supernova remnants we adopted the Cioffi, Mc Kee & Bertschinger (1988) cooling time, which is a function of density and metallicity of the ISM. On the other hand, we assumed that SN Ia can transfer all of their initial blast wave energy into the ISM. In fact, since type Ia

SNe originate from long living systems, their explosions occur in a medium already heated by SNII and therefore the cooling is negligible (see Recchi et al. 2001). Under these assumptions the $2 \cdot 10^{10} M_{\odot}$ model develops a galactic wind in the most external region (roughly 3 kpc from the center) at ~ 31 Myr and subsequently in the inner region (0-1 kpc) at ~ 200 Myr after the major episode of star formation has started. This situation is certainly compatible with what observed in MS 1512-cB58, where the outflowing gas is probably located in front of the star forming region at a distance of a few kpc (Pettini et al. 2001). The amount of stars formed at the time of the onset of the external wind is $\sim 1.1 \cdot 10^{10} M_{\odot}$ all over the galaxy with the stars being more concentrated towards the center. The models for 10^9 and $10^{11} M_{\odot}$ do not seem to reproduce the properties of MS 1512-cB58 since they predict too low and too high star formation rates at any galactic time, respectively, as evident in Figure 1. They also develop a wind in the most external regions too early and too late, respectively.

By means of our model we can predict the evolution of the abundances in the gas of H, He, N, O, Mg, Si, Fe versus time and metallicity. We adopted different sets of stellar yields in different stellar mass ranges: in particular, for massive stars ($M > 8 M_{\odot}$) the yields of Woosley & Weaver (1995), for low and intermediate mass stars ($0.8 \leq M/M_{\odot} \leq 8$) the yields of Renzini & Voli (1981) and for type Ia SNe the yields of Nomoto et al. (1984). It is worth noting that the model described above has been already compared with the observational properties of local ellipticals (see Pipino et al. 2002 and references therein), and they reproduce both colors and stellar chemical abundances of normal ellipticals.

3. Model results

In Figure 1 we show the predicted and observed star formation rates for MS 1512-cB58. The value quoted by Pettini et al. (2001) is $40 M_{\odot} yr^{-1}$ but we can consider a range of possible values of 20–80 $M_{\odot} yr^{-1}$, given the uncertainties connected with the derivation of the star formation rate. From the comparison between the predictions of the $2 \cdot 10^{10} M_{\odot}$ model (the best model) and the observed value, we infer an age for the galaxy inside one r_L of $\sim 100 \pm 60$ Myr. In Figures 2 and 3 we show the predicted [N/Fe], [Mg/Fe] and [Si/Fe] versus [Fe/H] and time, respectively, and compare them with the observed ones in MS 1512-cB58. The observed values have been corrected for possible dust depletion of Fe, although the underabundance of Fe-peak elements (relative to the undepleted S) cannot be entirely due to this effect. In fact, if that would be the case we should expect the abundances of Mg and Si to be also depleted, although to a lesser extent, relative to S. This is not what is observed since the ratios of Mg and Si relative to S are solar, as discussed by Pettini et al. (2001). We assumed that roughly half of the total Fe mass is hidden in grains (Pettini, private

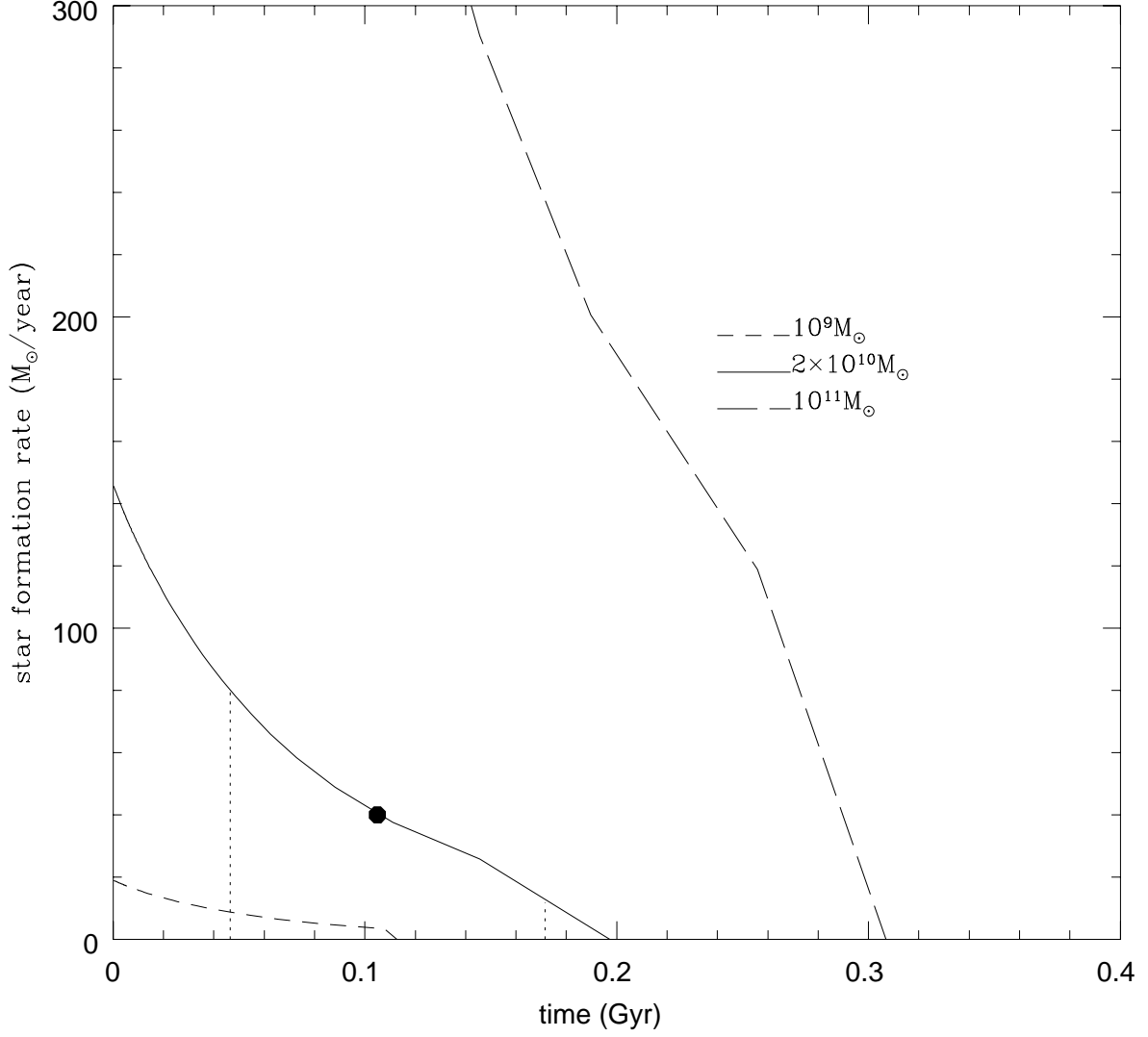


Fig. 1.— The average star formation rates predicted by our models until the onset of the galactic wind inside the optical radius of each galaxy. The dotted lines enclose the range for the possible values of the star formation rate and the full dot represents the value adopted by Pettini et al. (2001). From the comparison between observed and predicted star formation rate for the $2 \cdot 10^{10} M_{\odot}$ galaxy we suggest an age for MS 1512-cB58 of $\sim 100 \pm 60$ Myr.

communication). Therefore, the observed Fe abundance has been increased by roughly a factor of 2. As Figure 2 shows, the agreement between model predictions and observations is good for the $[\text{el}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ relationships, except for Mg which is predicted to be lower than observed. However, this is expected since all the available yields from massive stars underestimate the solar Mg abundance (e.g. Thomas, Greggio & Bender, 1998). Unlike the star formation rate, the abundance ratios in the gas are quite insensitive to the galaxy mass, whereas they depend strongly upon the nucleosynthesis, The IMF and timescales for the production of the different elements.

In Figure 3, where the abundance ratios are plotted as functions of galactic age and redshift, we indicate the observational values by dotted lines and see where these lines intercept the predicted curves. The interception gives an indication of the possible age of MS 1512-cB58. For $[\text{Mg}/\text{Fe}]$ and $[\text{Si}/\text{Fe}]$ the estimated galactic age can be as low as ~ 10 Myr, whereas for the $[\text{N}/\text{Fe}]$ ratio the inferred age is ~ 35 Myr, in excellent agreement with other independent estimates (Ellingson et al. 1996). From the $[\alpha/\text{Fe}]$ ratios we cannot exclude ages larger than 10 Myr but we can exclude ages larger than 300 Myr since the ratios at these times are considerably lower than observed. The high values of the $[\alpha/\text{Fe}]$ ratios indicate, in fact, that the object is younger than the typical timescale for the enrichment from SNe Ia (0.3-0.5 Gyr for ellipticals, Matteucci & Recchi, 2001). Nitrogen is also a good cosmic clock since it is mainly produced by low and intermediate mass stars, although massive stars contribute as well for a small amount of this element. As a consequence, N starts to be produced in a non negligible way only after 35 Myr (the lifetime of a $8 M_{\odot}$ star) while its bulk appears only after 300 Myr (the lifetime of a $2.7 M_{\odot}$). The ratio of N relative to any α -element is even more sensitive to age than the $[\alpha/\text{Fe}]$ ratio and this is because N is mainly a secondary element and therefore sensitive to the overall metallicity. The age- $[\text{Fe}/\text{H}]$ relationship predicted by the model for the $2 \cdot 10^{10} M_{\odot}$ galaxy suggests that $[\text{Fe}/\text{H}] = -0.85 \pm 0.1$ dex (the dust-corrected iron abundance) is reached at an age between 20 and 35 Myr. It is worth noting that we obtain a good agreement with observations also for the predicted $[\text{N}/\text{O}]$ ratio which is independent of dust depletion. In fact, we considered the oxygen abundance measured for MS 1512-cB58 by Teplitz et al. (2000) ($[\text{O}/\text{H}] = -0.35$ dex) together with the N abundance by Pettini et al. (2001) and compared the resulting $[\text{N}/\text{O}]$ vs. $[\text{O}/\text{H}]$ and time. In Figure 4 we show the two plots for the model galaxies which show that the observed $[\text{N}/\text{O}]$ ratio is compatible with an age between 25 and 30 Myr, in good agreement with that estimated from the $[\text{N}/\text{Fe}]$ ratio.

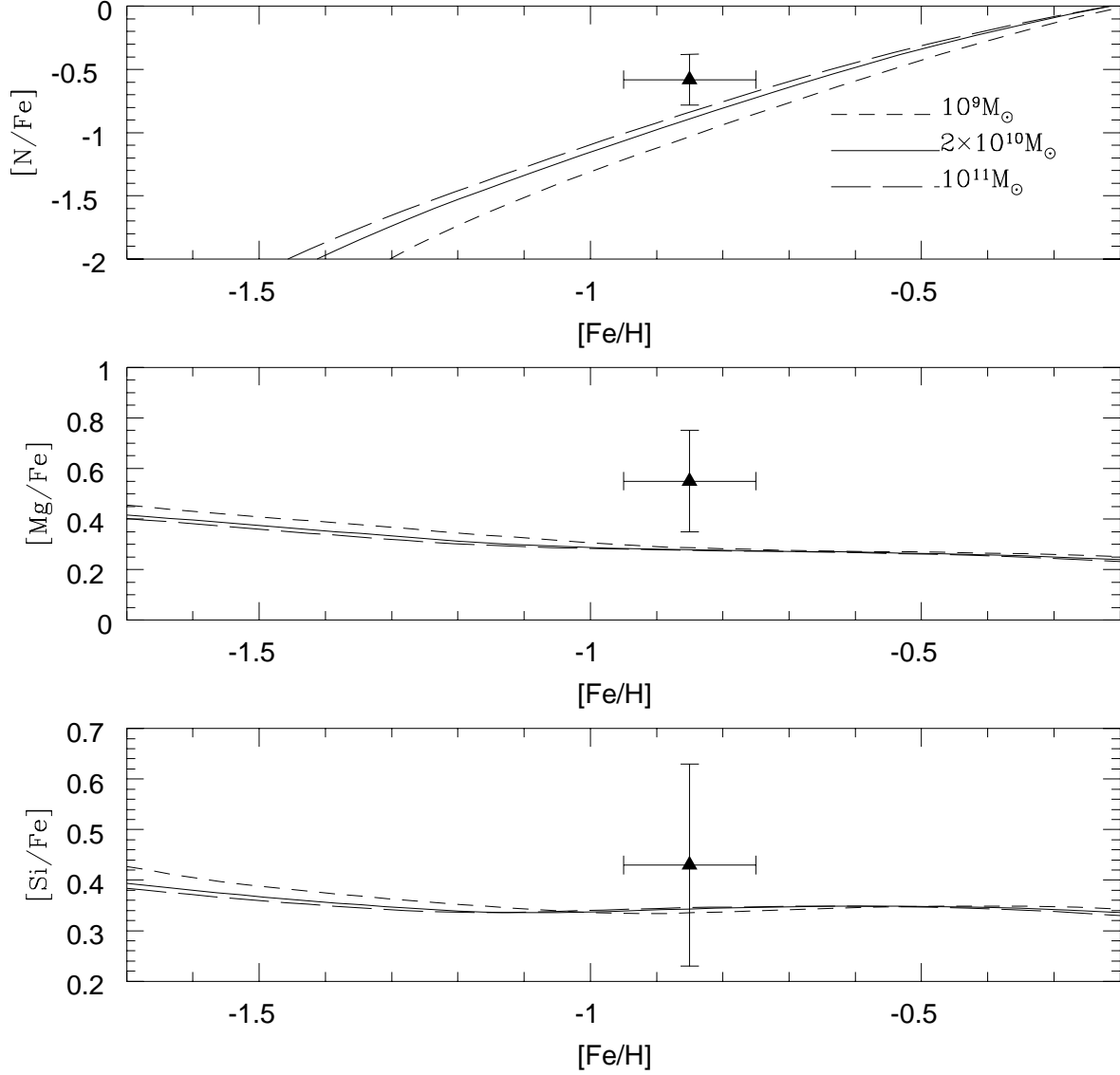


Fig. 2.— Predicted abundance ratios relative to the Sun versus $[\text{Fe}/\text{H}]$. The assumed solar abundances are the same adopted in Pettini et al. (2001). The observed values, dust corrected, are indicated. The luminous initial masses are indicated.

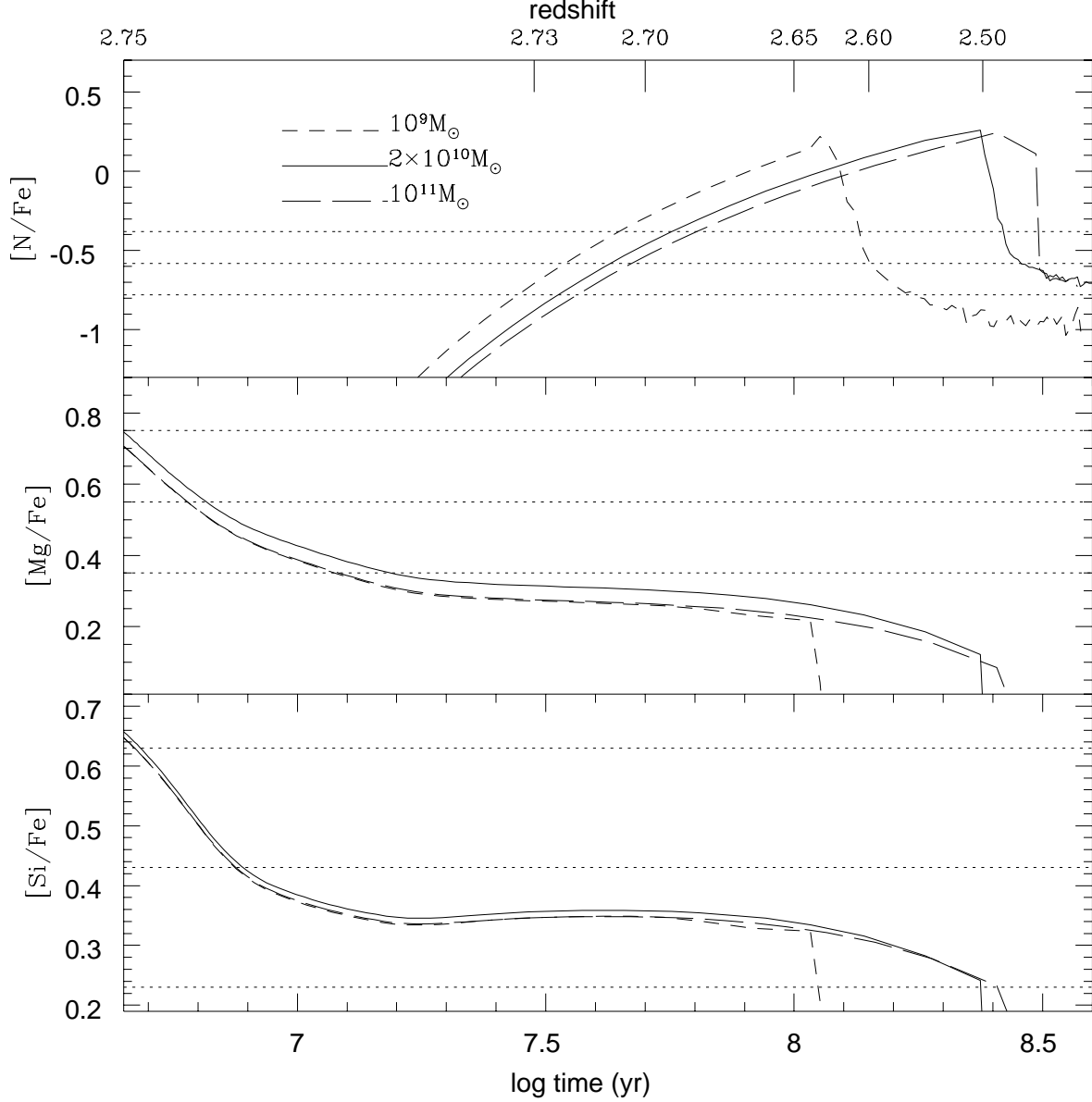


Fig. 3.— Predicted abundance ratios relative to the sun versus galactic age, for the different model galaxies. The models are as in Figure 2. The evolution of the abundance ratios in the external region of each model is very similar to that show here (inside an optical radius) but it develops a galactic wind earlier than the in central region (see text). The observed values and their errors are indicated by the dotted lines. The redshift is also indicated and the assumed cosmology is $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.70$.

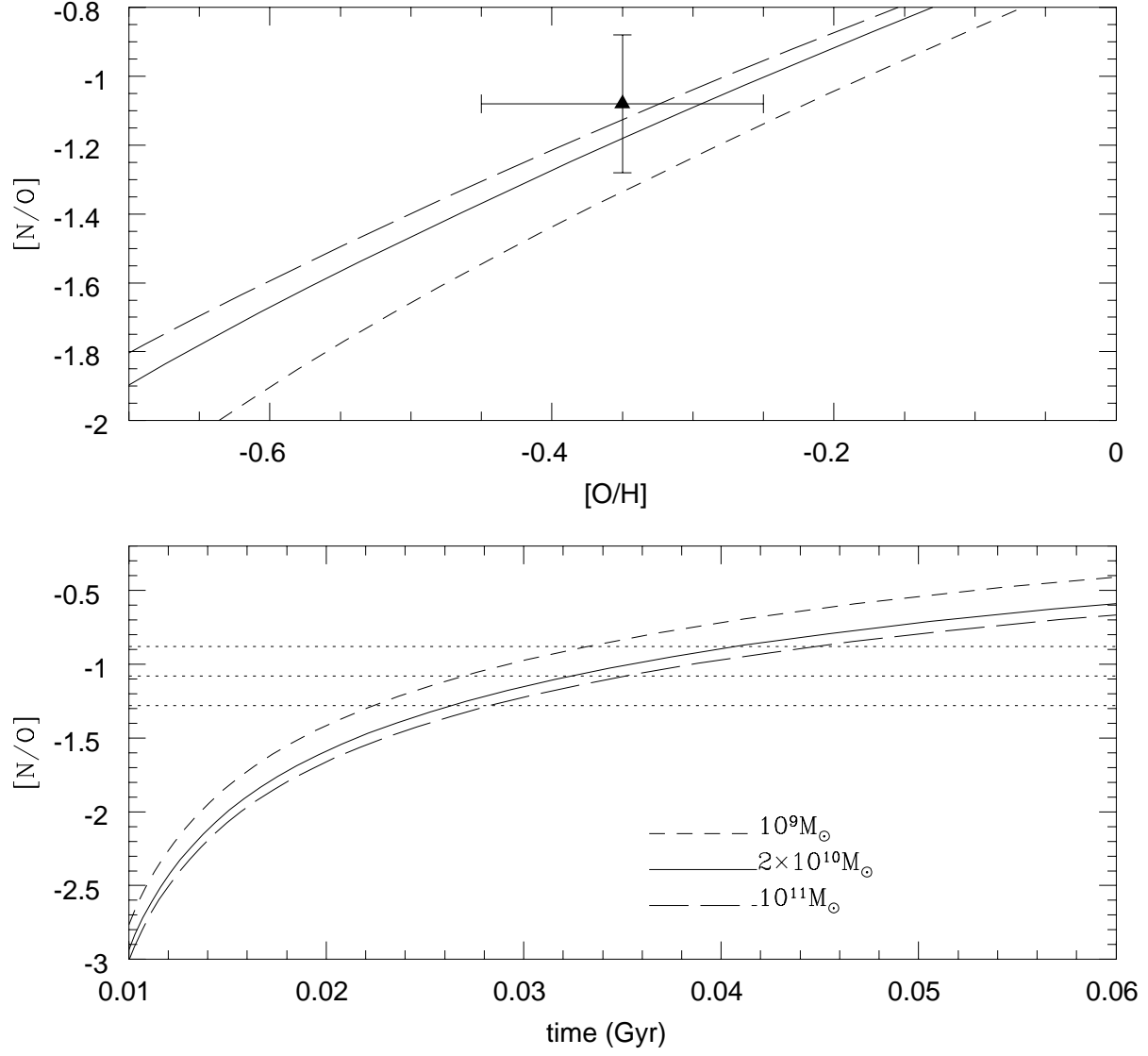


Fig. 4.— Predicted $[N/O]$ ratios versus $[O/H]$ and galactic age for the same models as in Fig.2 and Fig. 3. The observational point is shown as a full triangle. The N abundance is taken from Pettini et al. (2001) whereas the O abundance is from Teplitz et al. (2000).

4. Discussion and conclusions

In the previous section we have shown that a SN-driven wind multi-zone model for the formation and evolution of an elliptical galaxy with initial luminous mass of $2 \cdot 10^{10} M_{\odot}$, which develops a wind in the most external region (~ 3 kpc from the center) after ~ 31 Myr, can well reproduce the dust-corrected abundances measured by Pettini et al. (2001) in the Lyman-break galaxy MS 1512-cB58. The fit to the chemical abundances basically suggests that MS 1512-cB58 could be a very young elliptical galaxy with an age $20 \leq t_{sf} \leq 35$ Myr, experiencing its main starburst and starting to develop an outflow. Independent age estimates (Ellingson et al., 1996), based on the SED of this galaxy, suggest also an age of ~ 35 Myr, in good agreement with our independent estimate. The abundance ratios represent a strong constraint since they depend mainly upon the timescales of the production of the different chemical elements. On the other hand, the star formation rate depends strongly upon the galaxy mass and suggests a stellar mass of $\sim 1.1 \cdot 10^{10} M_{\odot}$ for MS 1512-cB58 and an age of $\sim 100 \pm 60$ Myr, but the observed value is affected by the assumed Hubble constant whereas chemical abundances are not, and therefore this age estimate should be considered less certain than that derived from the abundances. One of the uncertainties involved in this comparison is that the abundance of Fe is very probably affected by dust depletion but we do not know exactly how much depletion occurs. We assumed that the observed Fe abundance should be increased by a factor of two and this assumption produces values for the $[\alpha/\text{Fe}]$ ratios which are consistent with the $[\text{N}/\text{Fe}]$ ratio. On the other hand, if we took the observed abundances without correction the higher $[\alpha/\text{Fe}]$ ratios would suggest a younger age than what we have already inferred whereas from the higher $[\text{N}/\text{Fe}]$ ratio a much older one, thus leading to a less consistent picture. Moreover, our predicted $[\text{N}/\text{O}]$ vs. $[\text{O}/\text{H}]$ is also in good agreement with the observed values and neither N or O should be substantially affected by dust depletion. In any case, dust depletion can only be part of the cause for the measured Fe underabundance, which is mostly due to the young age of the galaxy as compared to the typical timescale for Fe production by type Ia SNe in ellipticals ($\sim 0.3 - 0.5$ Gyr, as shown by Matteucci & Recchi, 2001).

In conclusion, this letter supports the idea that LBGs are young galaxies which could be the progenitors of present day spheroids (ellipticals and bulges have very similar properties), although we cannot predict the precise fate of cB58. We also like to stress the importance of using abundance ratios as cosmic clocks for dating high redshift objects.

5. Acknowledgments

We are grateful to Max Pettini for his many important suggestions and to an anonymous referee for constructive comments.

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